4. Telecom Design for 1 Gbps, 500 Mbps, and 100 Mbps

The telecom system for Mars to Earth communication downlink is designed for three data rate capabilities for a Mars relay. The three design points are 1 Gbps, 500 Mbps, and 100 Mbps at the maximum range of 2.67 AU, corresponding to the furthest point from Earth for the relay satellite. This communication link is designed for a Ka-band downlink with 90 percent link availability.

4.1 Design Approach

The design approach for the links uses the reference link budget shown in appendix 4A. In designing the three links there is a trade space that is three dimensional namely, ground G/T satellite RF power and size of the satellite antenna. The link budget will calculate required EIRP for the required downlink data rate based on the assumptions in chapter 3 within the given trade space. The satellite assumptions used in the link budgets include 90 percent link availability, BPSK/QPSK (quaternary phase-shift keying) modulation and LDPC (low-density parity-check) coding 1 dB satellite antenna pointing loss, 60 percent antenna efficiency, and 0.5 dB circuit losses. The 1 dB antenna pointing loss will dictate the antenna pointing accuracy, which is dependent on antenna size. The pointing accuracy requirement will determine whether a fine-pointing mechanism would be needed, for example, when the antenna size becomes large enough such that the pointing accuracy derived by the ACS is insufficient to keep the pointing loss within 1 dB.

The Earth assumptions include receiver G/T based on the DSN array of 12-m antennas. Three G/T assumptions are used for the trade space based on the ground network options of 180-, 45-, and 12-element arrays. The combining loss of the array is assumed to be 0.5 dB, and the radio implementation loss is assumed to be 1 dB. A 34-m antenna is not assumed in the link, but it is important to note that the G/T of a 34-m antenna is similar to DSN array of approximately ten 12-m antennas.

The maximum bandwidth available for Ka-band downlink is 500 MHz; dual polarization is assumed in the link analysis where applicable. Other possible options, such as BEM, are evaluated in the cases where high data rates may be feasible within the 500-MHz bandwidth constraint. The tables in appendix 4B show various modulation techniques and required E_b/N_o for appropriate bandwidth efficient modulation. (It is important to observe that the table does not exhaust the available options. For example, trellis-coded modulation could be used to moderate data rates to save 3 to 6 dB in E_b/N_0.) The E_b/N_0 in these tables is used to calculate link budgets when the links require bandwidth-efficient modulation.

For a given EIRP requirement, the spacecraft parameters can be optimized to minimize the RF mass of the spacecraft. It is shown in the following equation that the spacecraft communications subsystem mass (m_{a+p}) can be minimized when the mass of the antenna (m_a) is the same as the power mass (m_p). Appendix 4C shows the derivation process of this mass minimization approach.

$$m_{a+p} = 2m_a = 2m_p = \lambda\sqrt{\frac{\mathrm{EIRP}\, d_a d_p}{L_t \eta_{ap} \pi}}$$

To minimize the mass of the spacecraft, the antenna system and power system masses will be equal. The antenna system mass comprises a reflector, a boom or a body mounting subsystem, portions of ADCS subsystem, and a fine-pointing subsystem. The antenna mass is estimated as a multiple of reflector area; the assumed density is 2 kg/m^2, that is, the antenna mass is computed using the formula $m_a = (\pi D^2 / 4) \cdot (2\,\mathrm{kg/m^2})$.

The power system includes the amplifier and other elements that provide power such as an amplifying device, Electronic Power Converter (EPC), solar array, and radiator subsystem.

Table 4–1 provides a power summary and indicates mass density for the power system as a function of output power. The power mass is computed based on the required output power using the power density factor shown in the last column of the table. In cases where dual polarization assumption is used, additional amplifier mass is included in the total power mass.

TABLE 4–1.—MARS POWER SUMMARY

Power (watts) and device type	Eff., %	Device		Electronic power convertor (EPC)		Solar array mass, 91 W/kg	Radiator mass, 67 W/kg	Total mass, kg	Power density, kg/W
		Mass, kg	Volume, cm^3	Mass, kg	Volume, cm^3				
100 (Helical Ka-band TWT)	60	2.5	3000	1.5	2250	1.8 kg	1 kg	6.8	0.068
180 (Helical Ka-band TWT)	55	2.5	3000	1.5	2250	3.6 kg	2.2 kg	9.8	0.054
250 (Helical Ka-band TWT)	50 to 55	3.0	3500	2.5	3375	5.0 kg	3.1 kg	13.6	0.054
1000 (By combining four 250 W TWTs using magic-T hybrid.)	45 to 50	13	15500	10	13500	22 kg	15 kg	60	0.060

4.2 Link Design and Trade Study

The first step is to use the design scenario assumptions as stated in chapter 2. A reference Ka-band link budget is constructed based on this scenario and a downlink Ka-band link design is performed for 1 Gbps, 500 Mbps, and 100 Mbps using these link budgets. The link budgets are calculated for link between Mars and Earth using the assumptions stated in chapter 3 and in section 4.1. Link budget analysis determines the spacecraft parameters for each ground option

and for each data rate design point at maximum Earth-Mars range, 2.67 AU. These parameter derivations also include the mass minimization approach indicated above. Further, when the range between Earth and Mars attains its minimum (0.38 AU), there is an increase in the link margin to about 14 to 17 dB that allows one to use that margin to trade among (1) increasing the downlink data rate; (2) reducing the number of antenna elements in the ground network; and (3) applying power conservation methods on the spacecraft.

A summary of results for three data rate design points (1 Gbps, 500 Mbps, and 100 Mbps) and three ground network options (180, 45, and 12 elements) are provided in tables 4–2, 4–3, and 4–4. The tables have a common structure. In table 4–2, for each ground network option, the spacecraft parameters for 1 Gbps at 2.67 AU are shown in the green highlighted rows in each table. Then the link is reevaluated for minimum range (cells highlighted in blue). Finally, the link is evaluated for BEM (cells highlighted in yellow). Tables 4–3 and 4–4 do the same for rates 500 and 100 Mbps, respectively. Each table provides a summary of the trade parameters and various options available for a given communication link, as discussed below.

Table 4–2 shows a summary of results for 1 Gbps for three different ground options. The results indicate that at 2.67 AU, a 4.5-m antenna and a 0.6-kW amplifier are required for a 180-element array ground network, whereas links with 45- and 12-element arrays require antennas and amplifiers of 6.2 m, 1.1 kW and 8.7 m, 2.2 kW, respectively.

TABLE 4–2.—SUMMARY OF RESULTS FOR 1 Gbps LINK (MARS TO EARTH)

DataRate (Mbps)	Range (AU)	SCAnt (m)	Ant Mass (kg)	SAntPtgEr (mdeg)	SCRFOut (kW)	Amp Mass (Kg)	SC-EIRP (dB)	Ground Network	GndGain (dB)	T_Gain (dB)	T_Mass (Kg)	Comments
Link Design 1Gbps at 2.67 AU with 180 element DSN-array (Dual polarization with each at 500Mbps)												
1000	2.67	4.5	31.80863	30	0.6	38.4	119.02	Array-180	92.95	211.97	70.208626	Dual Polarization (500Mbps)
9000	0.38	4.5	31.80863	30	0.6	38.4	119.02	Array-180	92.95	211.97	70.208626	Link Capability only (single polarization)
1000	0.38	4.5	31.80863	30	0.6	38.4	119.02	Array-4	76.42	195.44	70.208626	Dual Polarization (500Mbps)
2000	0.38	4.5	31.80863	30	0.6	38.4	119.02	Array-180	92.95	211.97	70.208626	BEM - 8PSK Dual Polarization (1Gbps)
2000	0.38	4.5	31.80863	30	0.6	38.4	119.02	Array-35	85.84	204.86	70.208626	BEM - 8PSK Dual Polarization (1Gbps)
Link Design 1Gbps at 2.67 AU with 45 element DSN-array (Dual polarization with each at 500Mbps)												
1000	2.67	6.2	60.38141	20	1.1	65.4	124.58	Array-45	86.93	211.51	125.78141	Dual Polarization (500Mbps)
15000	0.38	6.2	60.38141	20	1.1	65.4	124.58	Array-45	86.93	211.51	125.78141	Link Capability only w/ single polarization
1000	0.38	6.2	60.38141	20	1.1	65.4	124.58	Array-1	70.4	194.98	125.78141	Dual Polarization (500Mbps)
2000	0.38	6.2	60.38141	20	1.1	65.4	124.58	Array-45	86.93	211.51	125.78141	BEM - 8PSK Dual Polarization (1Gbps)
2000	0.38	6.2	60.38141	20	1.1	65.4	124.58	Array-8	79.43	204.01	125.78141	BEM - 8PSK Dual Polarization (1Gbps)
Link Design 1Gbps at 2.67 AU with 12 element DSN-array (Dual polarization with each at 500Mbps)												
1000	2.67	8.7	118.8936	14	2.2	124.8	130.56	Array-12	81.19	211.75	243.69357	Dual Polarization (500Mbps)
20000	0.38	8.7	118.8936	14	2.2	124.8	130.56	Array-12	81.19	211.75	243.69357	Link Capability only (single polarization)
2000	0.38	8.7	118.8936	14	2.2	124.8	130.56	Array-1	70.4	200.96	243.69357	Link Capability only (single polarization)
2000	0.38	8.7	118.8936	14	2.2	124.8	130.56	Array-12	81.19	211.75	243.69357	BEM - 8PSK Dual Polarization (1Gbps)
2000	0.38	8.7	118.8936	14	2.2	124.8	130.56	Array-2	73.41	203.97	243.69357	BEM - 8PSK Dual Polarization (1Gbps)

Notes:
a. 1-Gbps data rate assumes dual polarization with 500 Mbps for each polarization due to bandwidth constraint at Ka-band.
b. Green highlight with blue font is reference point to determine spacecraft parameters for link design at max. range of 2.67 AU.
c. Blue highlight indicates the trade between link capability and decrease in ground elements when range is reduced to 0.38 AU.
d. Yellow highlight indicates the link designed with BEM.
e. Fuchsia font indicates various options that can be chosen for minimum range of 0.38 AU between Earth and Mars; a 34-m antenna is similar to an array with 10 elements.
f. Results in the table include mass optimization.

There is an increase in spacecraft EIRP when the number of elements in the DSN array is reduced, resulting in an associated increase in the spacecraft antenna size and power requirements and the consequent mass. We have already observed that given a spacecraft design,

decreasing the range between Earth and Mars to its minimum (0.38 AU) results in an increase in the link margin that can be used to trade between increasing the data rate and reducing the number of ground-array elements. As seen in the table, a 180-element ground array designed for 1 Gbps at 2.67 AU can support the same data rate at minimum range with just four of its elements. Or, with a 180-element array, the link could theoretically support 9 Gbps by scaling the modulation waveform. But due to the bandwidth constraint of 500 MHz, this scaling cannot work; a BEM is required.

With BEM chosen from the appendix D table, the link can support at most 2 Gbps, since the required E_b/N_0 increases with BEM and the power requirement doubles in doubling the data rate. A more exhaustive modulation search might yield a further data rate increase. The results also indicate that regardless of the ground network configuration, a link designed for 1 Gbps at maximum range will not achieve a data rate increase of 14 dB at minimum range. Though the link has the power capability to support more than 2 Gbps, the combination of bandwidth constraints and the increased E_b/N_0 required for BEM limits the achievable data rate to the 1 to 2 Gbps region.

Table 4–3 shows a comparable summary of results for a 500-Mbps maximum range design. As seen from the results, a 3.9-m antenna with a 0.45-kW amplifier is required to design for a 2.67 AU and a 180-element array. The spacecraft parameters change to 5.3 m, 0.8 kW and 7.4 m, 1.6 kW for 45- and 12-element arrays, respectively. As before, the impact of a reduction on array elements is an increase in the spacecraft EIRP and other parameters. The result for minimum range communications is consistent; support of data rates 500 MHz to 2 Gbps, again due to the bandwidth constraint and the BEM-induced increase in E_b/N_0.

TABLE 4–3.—SUMMARY OF RESULTS FOR 500 Mbps LINK (MARS TO EARTH)

DataRate (Mbps)	Range (AU)	SCAnt (m)	Ant Mass (kg)	SAntPtgEr (mdeg)	SCRFOut (kW)	Amp Mass (Kg)	SC-EIRP (dB)	Ground Network	GndGain (dB)	T_Gain (dB)	T_Mass (Kg)	Comments
Link Design 500Mbps at 2.67 AU with 180 element DSN-array (Dual polarization with each at 250Mbps)												
500	2.67	3.9	23.89181	40	0.45	29.7	115.69	Array-180	92.95	208.64	53.591812	Dual Polarization (250Mbps)
4000	0.38	3.9	23.89181	40	0.45	29.7	115.69	Array-180	92.95	208.64	53.591812	Link Capability only (single polarization)
1000	0.38	3.9	23.89181	40	0.45	29.7	115.69	Array-8	79.43	195.12	53.591812	Dual Polarization (500Mbps)
500	0.38	3.9	23.89181	40	0.45	29.7	115.69	Array-4	76.42	192.11	53.591812	Dual Polarization (250Mbps)
2000	0.38	3.9	23.89181	40	0.45	29.7	115.69	Array-180	92.95	208.64	53.591812	BEM - 8PSK Dual Polarization (1Gbps)
Link Design 500Mbps at 2.67 AU with 45 element DSN-array (Dual polarization with each at 250Mbps)												
500	2.67	5.3	44.12367	25	0.8	48.6	121.72	Array-45	86.93	208.65	92.723669	Dual Polarization (250Mbps)
8000	0.38	5.3	44.12367	25	0.8	48.6	121.72	Array-45	86.93	208.65	92.723669	Link Capability only (single polarization)
1000	0.38	5.3	44.12367	25	0.8	48.6	121.72	Array-2	73.41	195.13	92.723669	Dual Polarization (500Mbps)
500	0.38	5.3	44.12367	25	0.8	48.6	121.72	Array-1	70.4	192.12	92.723669	Dual Polarization (250Mbps)
2000	0.38	5.3	44.12367	25	0.8	48.6	121.72	Array-45	86.93	208.65	92.723669	BEM - 8PSK Dual Polarization (1Gbps)
2000	0.38	5.3	44.12367	25	0.8	48.6	121.72	Array-16	82.44	204.16	92.723669	BEM - 8PSK Dual Polarization (1Gbps)
Link Design 500Mbps at 2.67 AU with 12 element DSN-array (Dual polarization with each at 250Mbps)												
500	2.67	7.4	86.01681	18	1.6	91.8	127.62	Array-12	81.19	208.81	177.81681	Assume Dual polarization with
11000	0.38	7.4	86.01681	18	1.6	91.8	127.62	Array-12	81.19	208.81	177.81681	Link Capability only (single polarization)
1000	0.38	7.4	86.01681	18	1.6	91.8	127.62	Array-1	70.4	198.02	177.81681	Dual Polarization (250Mbps)
2000	0.38	7.4	86.01681	18	1.6	91.8	127.62	Array-12	81.19	208.81	177.81681	BEM - 8PSK Dual Polarization (1Gbps)
2000	0.38	7.4	86.01681	18	1.6	91.8	127.62	Array-4	76.42	204.04	177.81681	BEM - 8PSK Dual Polarization (1Gbps)

Notes:

a. 1-Gbps data rate assumes dual polarization with 500 Mbps for each polarization due to bandwidth constraint at Ka-band.

b. Green highlight with blue font is reference point to determine spacecraft parameters for link design at max. range of 2.67 AU.

c. Blue highlight indicates the trade between link capability and decrease in ground elements when range is reduced to 0.38 AU.

d. Yellow highlight indicates the link designed with BEM.

e. Fuchsia font indicates various options that can be chosen for minimum range of 0.38 AU between Earth and Mars; a 34-m antenna is similar to an array with 10 elements.

f. Results in the table include mass optimization.

Table 4–4 shows a summary of results for 100 Mbps for three different ground options for DSN array. The results for antenna size and power follow the pattern seen in the prior two tables. With regard to link capability at range 0.38 AU, the results remain consistent with previous one in that the link can support no more than 2 Gbps due to bandwidth and E_b/N_0 constraints.

TABLE 4–4.—SUMMARY OF RESULTS FOR 100 Mbps COMMUNICATION LINK MARS TO EARTH

DataRate (Mbps)	Range (AU)	SCAnt (m)	Ant Mass (kg)	SAntPtgEr (mdeg)	SCRFOut (kW)	Amp Mass (Kg)	SC-EIRP (dB)	Ground Network	GndGain (dB)	T_Gain (dB)	T_Mass (Kg)	Comments
Link Design 100Mbps at 2.67 AU with 180 element DSN-array												
100	**2.67**	**3**	14.13717	45	**0.26**	17.16	111.86	**Array-180**	92.95	204.81	31.297167	Single polarization transmit
1800	0.38	3	14.13717	45	0.26	17.16	111.86	Array-180	92.95	204.81	31.297167	Link Capability only (single polarization)
1000	**0.38**	3	14.13717	45	0.26	17.16	111.86	**Array-23**	88.53	200.39	31.297167	Dual Polarization (500Mbps)
100	0.38	3	14.13717	45	0.26	17.16	111.86	Array-4	76.42	188.28	31.297167	Single polarization transmit
1800	**0.38**	3	14.13717	45	0.26	17.16	111.86	**Array-180**	92.95	204.81	31.297167	BEM - 8PSK Dual Polarization (900Mbps)
Link Design 100Mbps at 2.67 AU with 45 element DSN-array												
100	**2.67**	**4.2**	27.70885	30	**0.5**	30.12	117.75	**Array-45**	86.93	204.68	57.828847	Single polarization transmit
3000	0.38	4.2	27.70885	30	0.5	30.12	117.75	Array-45	86.93	204.68	57.828847	Link Capability only (single polarization)
1000	**0.38**	4.2	27.70885	30	0.5	30.12	117.75	**Array-5**	77.39	195.14	57.828847	Dual Polarization (500Mbps)
100	0.38	4.2	27.70885	30	0.5	30.12	117.75	Array-1	70.4	188.15	57.828847	Single polarization transmit
1800	**0.38**	4.2	27.70885	30	0.5	30.12	117.75	**Array-45**	86.93	204.68	57.828847	BEM - 8PSK Dual Polarization (900Mbps)
Link Design 100Mbps at 2.67 AU with 12 element DSN-array												
100	**2.67**	**5.9**	54.67942	20	**1**	57.12	123.58	**Array-12**	81.19	204.77	111.79942	Single polarization transmit
4500	0.38	5.9	54.67942	20	1	57.12	123.58	Array-12	81.19	204.77	111.79942	Link Capability only (single polarization)
1000	**0.38**	5.9	54.67942	20	1	57.12	123.58	**Array-1**	70.4	193.98	111.79942	Dual Polarization (500Mbps)
2000	**0.38**	5.9	54.67942	20	1	57.12	123.58	**Array-12**	81.19	204.77	111.79942	BEM - 8PSK Dual Polarization (1Gbps)

Notes:
a. 1-Gbps data rate assumes dual polarization with 500 Mbps for each polarization due to bandwidth constraint at Ka-band.
b. Green highlight with blue font is reference point to determine spacecraft parameters for link design at max. range of 2.67 AU.
c. Blue highlight indicates the trade between link capability and decrease in ground elements when range is reduced to 0.38 AU.
d. Yellow highlight indicates the link designed with BEM.
e. Fuchsia font indicates various options that can be chosen for minimum range of 0.38 AU between Earth and Mars; a 34-m antenna is similar to an array with 10 elements.
f. Results in the table include mass optimization.

Some key results in the tables can be displayed graphically. Figure 4–1 shows how antenna size varies versus data rate, parametric in the ground array size. Figure 4–2 indicates an amplifier range from 0.25 to 2.2 kW over the same range of rates. Both figures pertain to a Mars-to-Earth communication link at 2.67 AU for three ground network array size options.

The next four figures explore the achievable data rate versus link margin (or distance), parametric in the data rate selected for maximum range. These calculations show the extent to which the spacecraft may allocate its additional link margin to more bandwidth-efficient modulation methods that increase the data rate. These results assume that (1) the exploration bandwidth allocated for the Mars satellite relay transmission to Earth is fixed at 500 MHz; (2) the EIRP has been designed for the maximum distance to Earth; and (3) all of this available EIRP is utilized to maximize the data rate when the range is less than the maximum. Of course, the link margin achieved by decreased range could be used in other advantageous ways; clearly reduced data rates occur if some of the EIRP margin is used to reduce either the Earth G/T and/or spacecraft (S/C) transmit power.

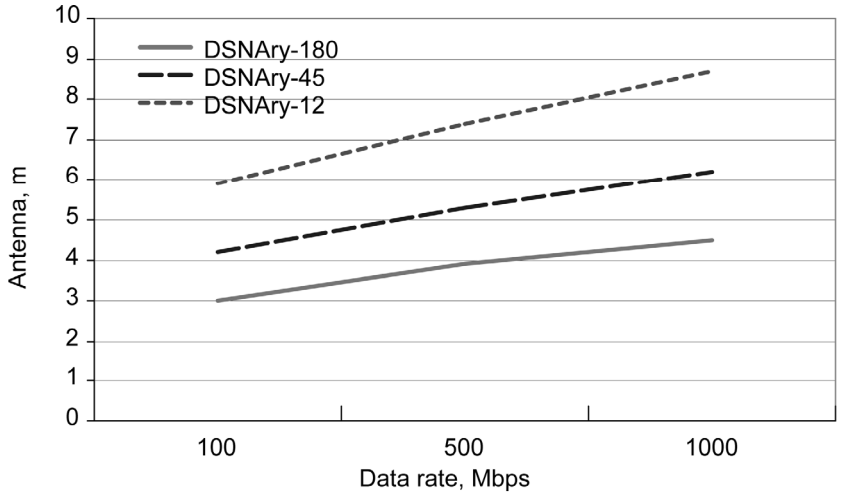

Figure 4–1.—Antenna size versus data rate for three ground network options.

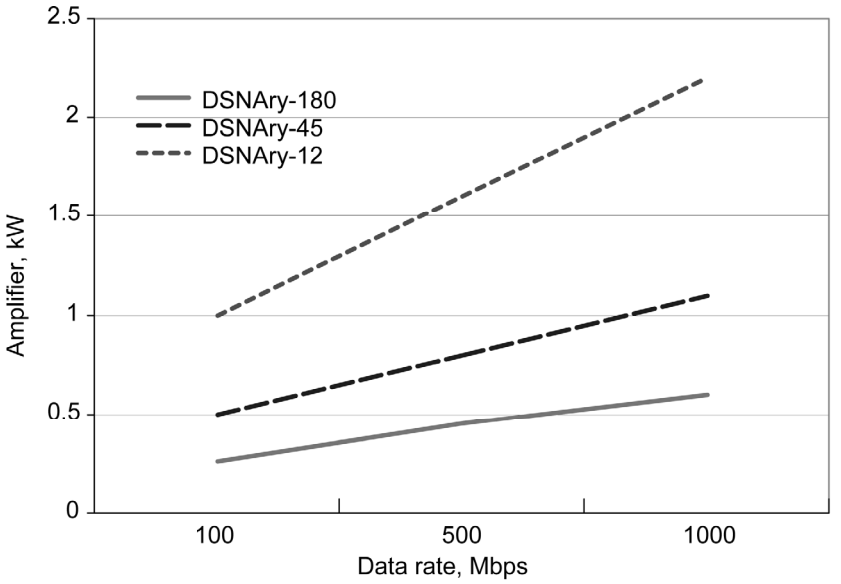

Figure 4–2.—Amplifier power versus data rate for three ground network options.

A set of seven modulation types described parametrically in table 4–5 are considered in this exercise. In figures 4–3 through 4–5 we show the data rates that can be achieved by each modulation type, excluding those that did not turn out to yield the highest data rate at any margin value within the range considered. Thus, for example, figure 4–3, which corresponds to a design for 1 Gbps at maximum range, has only five curves; two of the modulations, 8-PSK rate 3/4 (#2) and uncoded QPSK (#6) are dropped because there exists a better alternative at every distance. Similarly, figures 4–4 and 4–5, for 500 and 100 Mbps rates at maximum distance, exhibit only four and three modulations, respectively.

TABLE 4–5.—MODULATION TYPES SELECTED FOR COMPUTING MAXIMUM ACHIEVABLE DATA RATE VERSUS DISTANCE, OR EQUIVALENTLY, MARGIN

Number	Modulation	Coded bits/symbol	Code rate	Spectral efficiency (info. bits/symbol)	E_b/N_0, dB
1	QPSK	2	1/2	1	2.2
2	8-PSK	3	3/4	9/4	6.4
3	8-PSK TCM	3	2/3	2	4.0
4	8-PSK TCM	3	3/4	9/4	5.1
5	8-PSK TCM	3	5/6	5/2	6.2
6	QPSK	2	1	2	9.6
7	8-PSK	3	1	3	13.2

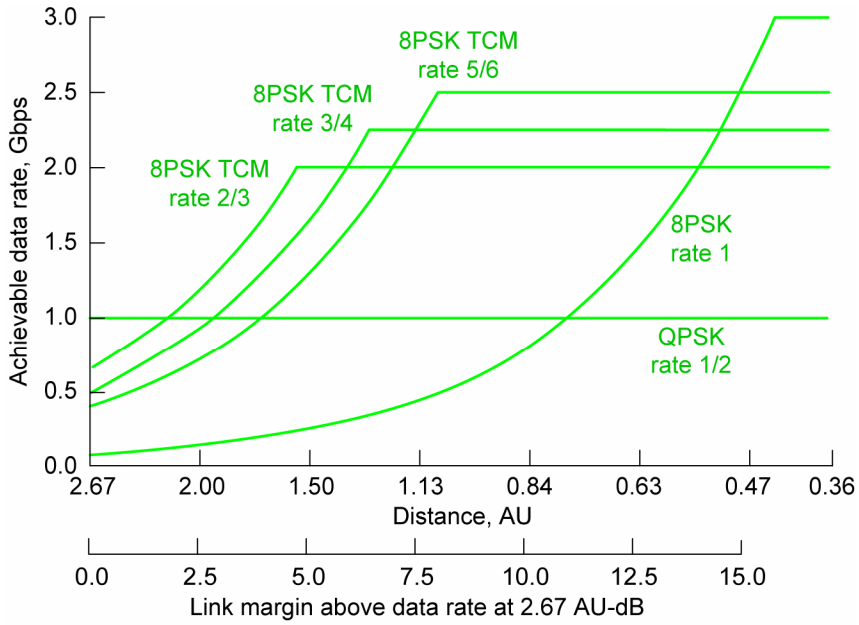

Figure 4–3.—Achievable data rate versus link margin above the 2.67 AU level for 1.0 Gbps at maximum range.

The data rate curves increase in proportion to the linear margin until they reach the point at which their bandwidth fills the allocation; beyond this saturation data rate, additional margin yields no further rate increase.[6]

Figure 4–3 enables one to trace the data rate and modulation format evolution as increasing amounts of margin become available. When the design is for 1 Gbps at 2.67 AU, the S/C can transmit rate-1/2 encoded QPSK modulation, as long as dual polarization is used to achieve 500 Mbps per polarization. Since the modulation fills the 500-MHz spectrum, additional margin

[6]Nyquist bandwidth is taken as the criterion for determining the saturation data rate. For example, modulation #3, 8-PSK TCM, rate 2/3, transmits 2 information bits per symbol. Multiplying this by the available bandwidth 500 MHz yields a peak rate of 1 Gbps within the bandwidth. On the figures, the saturation rate is double this value due to the assumption of dual polarization usage.

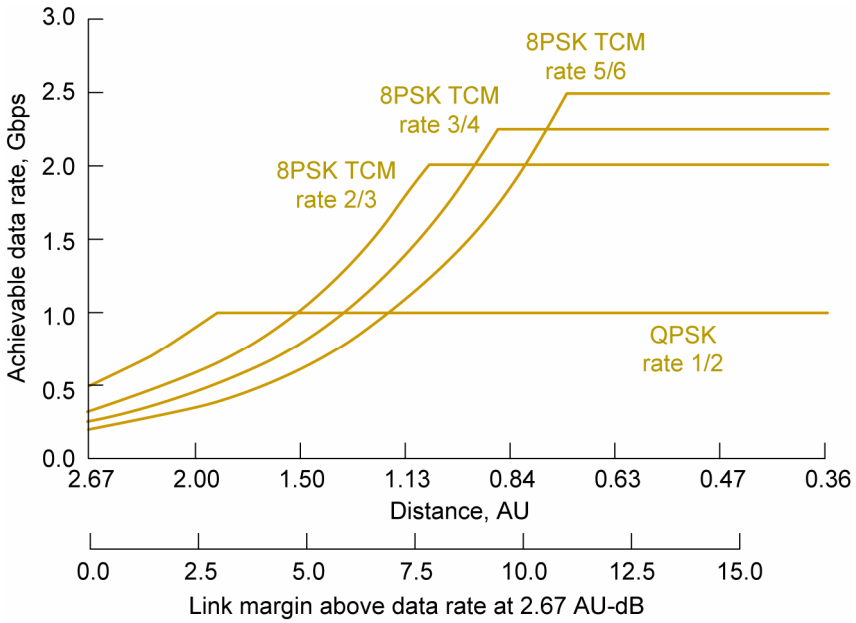

Figure 4–4.—Achievable data rate versus link margin above the 2.67 AU level for 500 Mbps at maximum range.

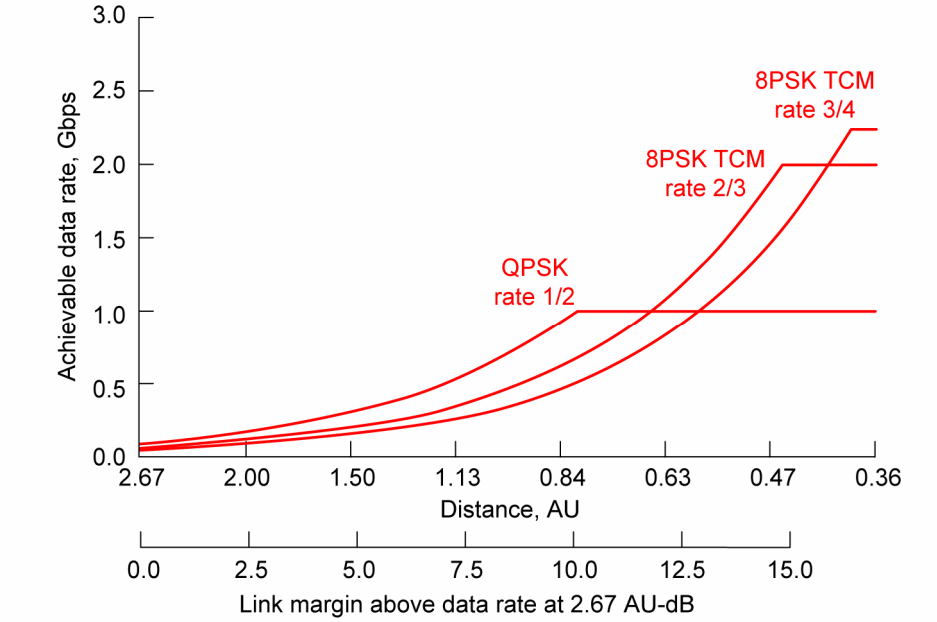

Figure 4–5.—Achievable data rate versus link margin above the 2.67 AU level for 100 Mbps at maximum range.

cannot be used to increase the data rate until there is sufficient signal strength to permit substitution of a more bandwidth-efficient modulation. As the margin increases above 1.5 dB, rate-3/4 encoded 8-PSK Trellis-coded modulation (TCM) may be substituted, first at the same data rate (1 Gbps) and then a rate increasing with margin. This modulation, also, eventually consumes all available bandwidth, negating any further data rate increase from it at higher margins. The other three modulations shown in the figure all come into play at other margin levels.

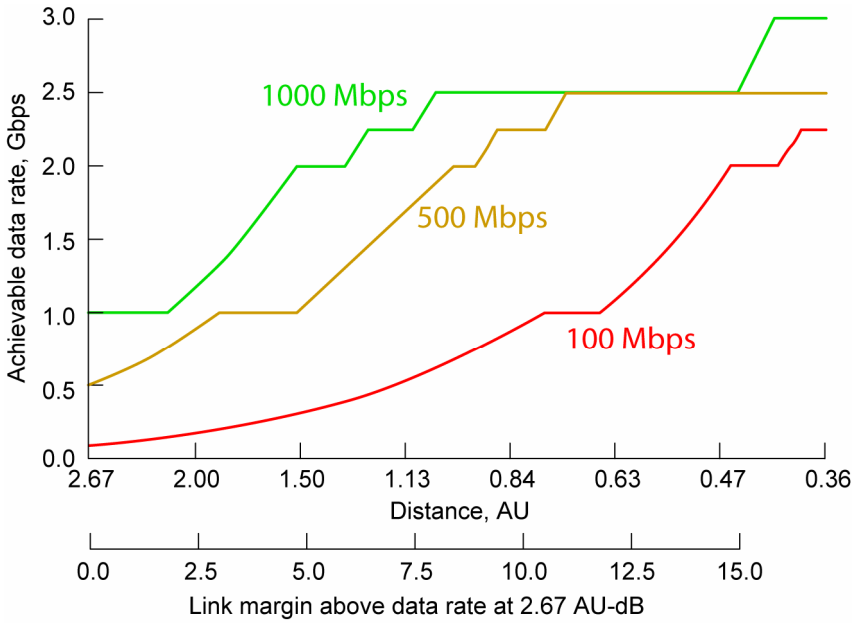

Figure 4–6.—Peak data rates achievable using the best modulation method at each value of margin, parametric in data rate at distance 2.67 AU.

Similar behaviors are shown for the two lower data rates. It may seem surprising that even by designing for one of the lower rates at the 2.67 AU distance, the additional margin still supports substantial gains in data rate.

Figure 4–6 collects the information from the three prior figures by presenting the peak data rate envelope that is found using the modulation that proves most efficient at each value of margin. There are undoubtedly other modulation/coding schemes that would fill in some of the data rate plateaus. A 16-PSK, rate 3/4 TCM would achieve a 3-Gbps peak rate, but could get there at a value of margin lower than what is found for uncoded 8-PSK.

4.3 Observations Concerning the Link Design Trade Study

The trade study in section 4.2 considers Mars-Earth communication links of 1 Gbps, 500 Mbps, and 100 Mbps for three DSN-array ground options of 180, 45, and 12 elements. The following observations can be made:

1. EIRP requirement results increase as the numbers of ground elements are reduced. With this increase in EIRP, there is an associated increase in antenna size, amplifier size, and the RF mass of the spacecraft.
2. BEM usage assists in increasing the data rate only to about 3 Gbps when the range is minimum, that is, 0.38 AU.
3. It is difficult to convert new-found link margin into a corresponding data rate increase in a bandwidth-constrained environment. The margin must be used to support the rate increase itself as well as the SNR inefficiency encountered in transitioning to a more bandwidth-efficient (hence, less power-efficient) method of modulation and coding.

4. The ultimate data rate that may be achieved at the point of closest approach is a rather weak function of the initial rate designed for 2.67 AU distance. Our examples span a factor of 10 in maximum distance design rate, and yet the rates achieved when the full 17-dB margin is in effect, all saturate at or near 3 Gbps. However, the lower the design rate, the more slowly the 3-Gbps asymptote is approached.
5. For the Mars example, the 17-dB range of signal variation is not wide enough to allow the eventual introduction of any nonconstant envelope modulations such as quadrature amplitude modulation (QAM). The high E_b/N_0 requirements of these highly bandwidth-efficient modulation methods preclude their use because the margin cannot support them. As an example, it takes 23-dB margin before rate-3/4 encoded 64 QAM can be used to drive the data rate to 4 Gbps. Trellis-coded PSK can achieve close to this with a constant-envelope waveform.
6. The ability to increase data rate as the spacecraft comes closer to Earth can be used to increase the average data return, or throughput, achieved on a mission, as long as a large fraction of the data is highly delay tolerant.

4.4 Conclusions Concerning the Link Design Trade Study

A high-rate Ka-band downlink is feasible between Earth and Mars at a maximum range of 2.67 AU. This is feasible for all the design points of 1 Gbps, 500 Mbps, and 100 Mbps.

From all the link analysis for the various options, it was determined that a spacecraft antenna, ranging in the size from 3 to 9 m would be needed for the Mars-Earth Ka-band downlink, with associated power requirements of 0.25 to 2.2 kW. Chapters 5 and 6 discuss more on the antenna and power technologies to determine their feasibility.

When a link is designed for any one of these data rates at maximum range, there is an increase in link capability with the varying Earth-Mars distance. This variation allows one to take advantage of the link margin observed by trading between various options such as an increase in data rate or reducing the number of ground elements. The increase in the data rate is constrained by bandwidth limitation of 500 MHz, thus requiring bandwidth-efficient modulation. The option for BEM was studied and it was determined that though the increase in the link margin is about 14 to 17 dB from maximum range to minimum range between Earth to Mars, this does not directly translate into similar data rate increase. The maximum achievable data rate at the minimum range is 3 Gbps. This increase to 3 Gbps is beneficial if the original link is designed for 100 Mbps at maximum range. But for the higher initial data rate designs it might be better to expend the margin by reducing the number of ground elements or reducing the spacecraft power consumption while keeping the data rate unchanged.